ON THE USE OF TETROONS FOR THE ESTIMATION OF ATMOSPHERIC DISPERSION ON THE MESOSCALE

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[Manuscript received March 5, 1962; revised April 6, 1962]

ABSTRACT

Atmospheric dispersion in the crosswind direction from a continuous point source is estimated as a function of downwind distance through the use of running-mean-velocity variance statistics obtained from radar-tracked constant volume balloon (tetroon) flights over ocean and desert. On the average, the tetroon data indicate that, at a height of 2,000–3,000 ft. and in the range 0.4–1.4 n. mi., the lateral dispersion is proportional to the 0.8 power of the downwind distance, whereas the vertical dispersion is proportional to the 0.5 power of the downwind distance. In both dimensions the power becomes less at larger distances and with increasing atmospheric stability. The relatively small power in the case of vertical dispersion is partly associated with vertical oscillations of period near 10 min., a period which appears to vary with lapse rate in the theoretically prescribed manner. In a few cases this periodicity is sufficiently pronounced so as to yield a small decrease in vertical dispersion with downwind distance and time (pinching effect) but this may be due to insufficient flight duration. A comparison of the dispersion estimated from tetroon flights, and the dispersion determined by fluorescent dye techniques, suggests that the tetroons yield reasonable dispersion statistics. If further experiments show that this is indeed the case, it is proposed that the relatively cheap tetroons be utilized to develop a dispersion climatology and that they be made available for an immediate estimate of trajectory and dispersion in the case of an accidental release of contaminant.

1. INTRODUCTION

It is well known that dispersion or diffusion estimates are most naturally made utilizing Lagrangian data, that is, data derived from the trajectories of individual air parcels. Formal expressions of diffusion all involve the Lagrangian correlation or spectrum and therefore it is not surprising that much of the recent work in diffusion has been concerned with estimating these Lagrangian statistics from the more easily obtained Eulerian (fixed-point) statistics. Inasmuch as there is strong evidence that constant volume balloons (tetroons) closely follow the 3-dimensional air motion, it is natural to try to eliminate the problem of Eulerian-Lagrangian relationships and to estimate atmospheric dispersion directly from tetroon data. This has been done using tetroon flights from Wallops Island in Virginia [1] and Yucca Flat in Nevada [2] and utilizing a variant of Taylor's dispersion equation. In the following, crosswind (vertical and lateral) dispersions so obtained are correlated with atmospheric conditions and are compared with dispersion estimates obtained by more conventional techniques. The purpose of the paper is to show that tetroons represent a feasible and logical means of estimating the atmospheric dispersion from a continuous point source, particularly on the mesoscale.

2. PROCEDURES AND PROBLEMS

A familiar method for estimating the dispersion from a continuous point source involves the use of Taylor's equation, which relates crosswind particle variance to the product of crosswind velocity variance and double integral of the Lagrangian correlation in the crosswind direction. It has been shown by Pasquill [13], Gifford [6], and others that the running mean-variance statistic

$$\overline{Y^2(T)}=\overline{v_T'^2}\,T^2 \qquad (1)$$

is in theory fully equivalent to Taylor's dispersion equation and in some ways is better behaved. In equation (1), $\overline{Y^2(T)}$ is the crosswind particle variance after travel time T and $\overline{v_T'^2}$ is the crosswind variance of the (Lagrangian) velocity averaged over travel time T. Basically this is a distance-equals-velocity-times-time equation but implicit in it is the information that for a short travel time oscillations of all frequency contribute to the dispersion whereas for long travel times the low frequency oscillations dominate the dispersion. While it is intuitively obvious that this should be so, it is analytically expressed in equation (1) by the damping effect of longer and longer averaging times upon velocity oscillations of lower and lower frequency.

If Lagrangian data are available, equation (1) appears an extremely easy way of estimating dispersion, because all that is required is velocities averaged over time intervals equal to the travel time for which the dispersion is desired and the corresponding variance statistics. There are, however, subtle difficulties involved in the use of even so simple an expression as equation (1), partly due to the assumptions on which the equation is based and partly to limitations in the data now available to substitute in the equation. An assumption basic to Taylor's dispersion equation, and equation (1) as well, is that the turbulence is uniform in space (homogeneous) and steady in time (stationary). If these conditions do not hold, then the displacement statistics of a single particle observed a large number of times will not be identical to the displacement statistics of a large number of particles passing a given fixed point (source) in succession, and some error will be introduced in dispersion estimates obtained through the use of equation (1). Another difficulty arises because the atmosphere possesses all scales of motion up to the hemispheric scale and consequently the value of the velocity variance has no upper limit, but will increase as the time or space scale is increased. This effect was evident in the Yucca Flat flights, where successive tetroon releases during the day indicated a veering of the wind with approximately a pendulum-day period. The velocity variance associated with such a slow oscillation was, of course, not at all evident in the individual tetroon flights of relatively short duration and consequently, at least in this case, dispersion estimates from the individual flights would not be expected to apply to long release and sampling times. This problem can be minimized by estimating the dispersion only for travel times much smaller than the sampling time or balloon travel time.

The final difficulty mentioned here involves the manner in which the statistics are obtained. Theoretically, the bar over the velocity variance in equation (1) represents an ensemble average or average over many different trials random in space and time. However, owing to the few tetroon flights so far made, such statistics are simply not available at this time, and in this paper dispersion estimates have been obtained from individual tetroon flights. It should be noted, however, that for the practical estimation of dispersion the truly random trails may even be misleading since, as will be shown, individual values of the variance are widely different depending upon atmospheric stability conditions. Evidence will be presented later suggesting that the dispersion obtained from an individual flight is fairly representative, but in any event this difficulty can be overcome in the future, and the necessary statistics obtained, either by dividing long flights into independent segments or by making a number of short flights simultaneously or in succession.

For the purposes of this paper, the dispersion was estimated by substituting in equation (1) vertical and lateral velocity variances obtained from tetroon velocities averaged over travel times no greater than one-fifth the flight duration at altitude. These variances were obtained from a computer program developed by the Environmental Meteorological Research Project of the U.S. Weather Bureau. As shown by Pack [10], a comparison of the dispersion estimated from Taylor's equation and equation (1) suggests that a maximum travel time of one-tenth the flight duration would have been much more appropriate, but the tetroon flights were too short for such a statistically satisfying procedure At the longer travel times the dispersion estimates reported herein might be underestimates by at least 20 percent owing to this factor and, as discussed later, the influence of periodicities in the flow may have been overestimated thereby. The dispersion as a function of travel time so obtained has been converted to dispersion as a function of downwind distance by use of the mean velocity along the flight.

3. DISPERSION ESTIMATES

Figures 1 and 2 illustrate the ratios of standard deviation of lateral particle displacement and downwind distance, and standard deviation of vertical particle displacement and downwind distance, respectively, as functions of downwind distance along individual tetroon flights. The data in figures 1 and 2 have been plotted on log-log paper so that the power of the downwind distance to which the lateral and vertical dispersions are proportional may be estimated from the slope of the lines. The slope appropriate to a given power is shown in the lower left corner of both diagrams. Table 1 shows the conditions under which the tetroon flights were made and pertinent data concerning the flights themselves.

In figure 1 the dots (unstable conditions) and circles (stable conditions) represent lateral dispersion data obtained by Pasquill [14] at Cardington, England by means of airplane sampling of ground-released fluorescent dye. The triangles represent similar data obtained by Crozier and Seely [5] in New Mexico in generally unstable conditions. The following points are to be emphasized with regard to figure 1.

TABLE 1.—*Tetroon flight information and associated weather conditions*

Flight	Released		Mean flight level (ft.)	Mean speed (kt.)	Synoptic situation
	Date	Local time			
1*	1-11-60	1117	3,800	33	Post strong cold front.
3*	1-26-60	1407	3,000	17	Warm sector.
5*	1-28-60	0859	1,600	9	Weak cold front zone.
7*	1-28-60	1414	2,500	14	Post weak cold front.
8*	1-29-60	0914	2,800	3	Cool stagnant air.
1	9-19-60	1213	6,200	9	Typical Nevada summer regime.
2	9-19-60	1346	4,100	9	
6	9-19-60	2008	200	7	
7	9-20-60	0635	1,200	4	
9	9-20-60	1204	3,500	12	
14	9-21-60	0702	6,300	24	
15	9-21-60	0851	2,800	18	

NOTE.—Starred flights from Wallops Island over the sea, unstarred flights from Yucca Flat over the desert.

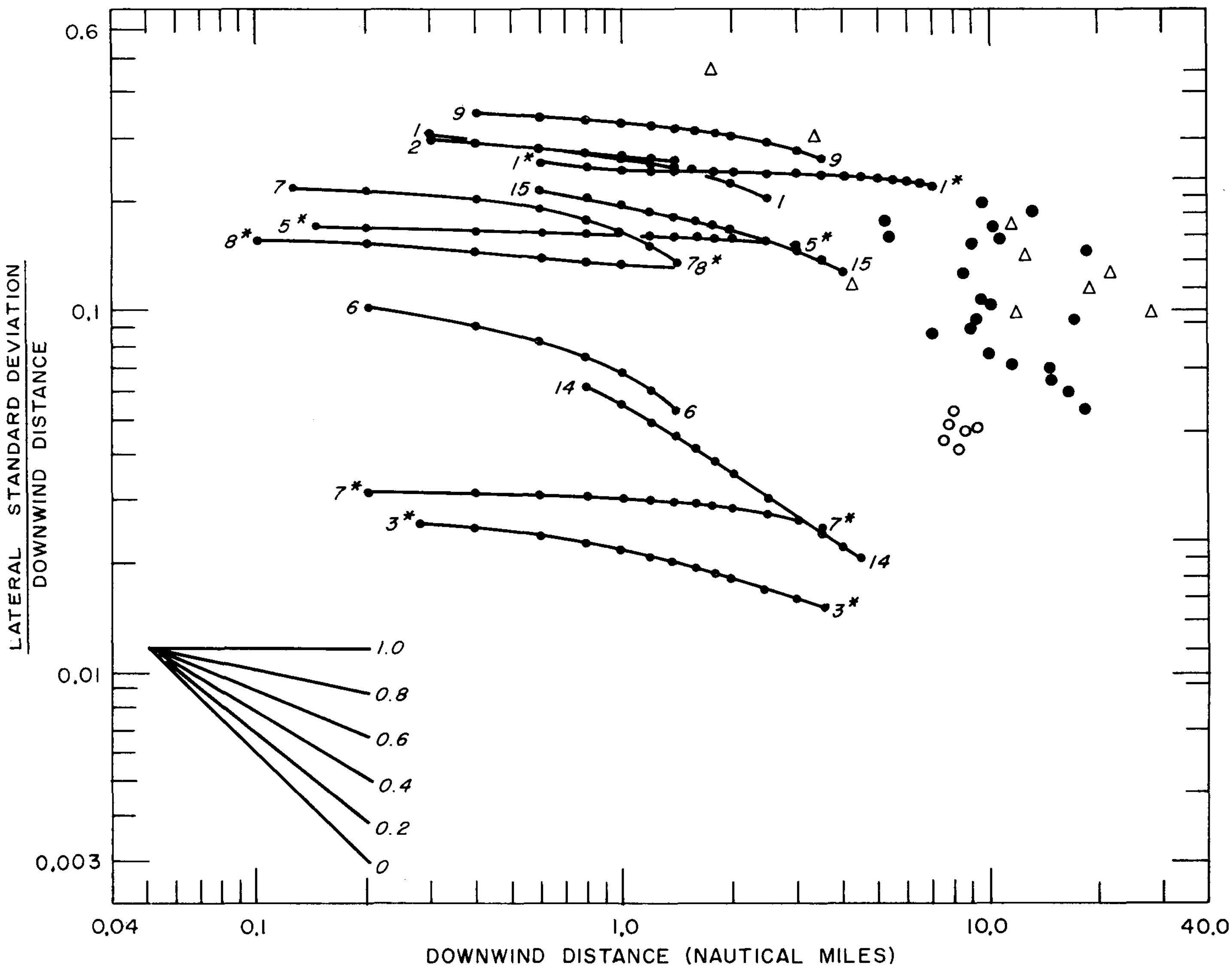

FIGURE 1.—Variation of the ratio of standard deviation of lateral particle displacement and downwind distance with downwind distance for individual tetroon flights. The dots (unstable conditions) and circles (stable conditions) indicate ground-released fluorescent dye results obtained at Cardington, England, while the triangles indicate results obtained in New Mexico by similar techniques in unstable conditions. The power of the downwind distance to which the lateral dispersion is proportional is shown by the slope of the lines in the lower left corner.

1. The similarity in the lateral dispersions estimated from flights 1 and 2 (released 1½ hours apart) and flights 1 and 9 (released at the same time one day apart) lends support to the representativeness of the dispersion derived from individual flights. See also figure 2 in this respect.

2. The tetroon data indicate that, at heights of 2,000–3,000 feet and distances of 0.1–10 n. mi., the ratio of standard deviation of lateral particle displacement and downwind distance varies from a value near 0.03 in relatively stable conditions over the sea to values exceeding 0.3 in unstable conditions over the desert.

3. At distances of 0.4–1.4 n. mi. the tetroon data yield, on the average, a lateral dispersion varying according to the 0.8 power of the downwind distance. However, this average power varies from a value of 0.9 at the shorter distance to 0.7 at the longer distance. The latter value may be an underestimate due to insufficient flight length.

4. The above power apparently decreases more rapidly with downwind distance in stable conditions than in unstable conditions. This is illustrated more clearly in figure 3, which shows the relationship between this power in the lateral and vertical directions, and the ratio of vertical or lateral dispersion and downwind distance. Since the latter parameter is a function of atmospheric stability, the power also appears to be a function of stability. One would estimate from figure 3 that, over the given distance and for the given height, the power in

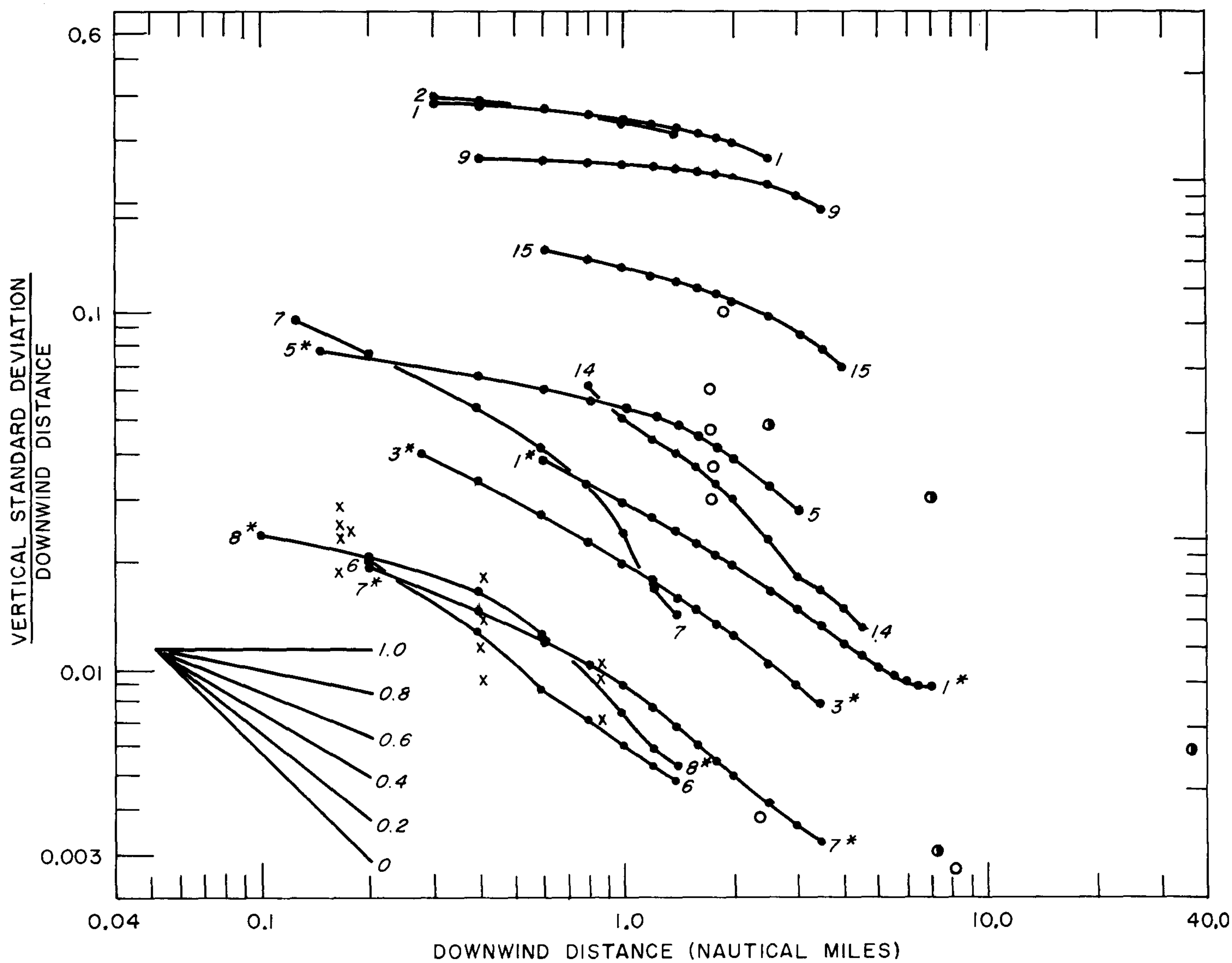

FIGURE 2.—Variation of the ratio of standard deviation of vertical particle displacement and downwind distance with downwind distance for individual tetroon flights. The dots (unstable conditions), half dots (intermediate conditions), and circles (stable conditions) indicate fluorescent dye results obtained at Cardington at heights near 2,000 feet; the crosses indicate results obtained near the ground at Hanford, Wash. in stable conditions. Otherwise, see figure 1 legend.

the case of lateral dispersion varies from about 0.9 in unstable conditions to about 0.7 in stable conditions, a result in fair agreement with that found by Cramer, Record, and Vaughan [4]. A possible danger in this deduction lies in the fact that the tetroon flights in stable conditions are, in general, somewhat shorter than the flights in unstable conditions. However, the dispersion as a function of distance derived from flight 2 (unstable conditions) and flights 6 and 7 (stable conditions) tends to confirm the finding for flights of equal length (fig. 1).

5. The release of fluorescent dye at ground level at Cardington under unstable conditions yields lateral dispersions in reasonable agreement with those derived from tetroon flights in unstable conditions. However, the over-water tetroon flights yield lateral dispersions considerably smaller than those found at Cardington under stable conditions, no doubt partly due to the effect of ground-induced mixing in the latter case. With respect to this possible ground effect, it is of interest that the fluorescent dye experiments in New Mexico suggested greater lateral dispersion than that found from tetroon flights in Yucca Flat at the time of maximum instability.

Turning now to figure 2, the dots (unstable conditions), circles (stable conditions) and half-dots (intermediate conditions) indicate vertical dispersion estimates obtained at Cardington by sampling, on barrage-balloon cables, fluorescent dye released from an airplane at a height near 2,000 ft. [16]. The crosses indicate results on vertical dispersion obtained by Hilst and Simpson [8] using similar techniques, except that the dye was released from a tower at a height of 185 ft. Remembering that at Cardington the data on lateral dispersion were obtained from ground-released fluorescent dye, one can see it is more justifiable to compare the vertical dispersion results obtained by tetroons and fluorescent dye than it is the lateral dispersion results. The following points are to be emphasized with regard to figure 2:

1. The tetroon data indicate that, at heights of 2,000–3,000 feet and distances of 0.1–10 n. mi., the ratio of standard deviation of vertical particle displacement and downwind distance varies from a value near 0.01 in relatively stable conditions over the sea to values exceeding 0.2 in unstable conditions over the desert. A low-level tetroon flight within the nocturnal inversion at Yucca Flat also indicates a ratio near 0.01.

2. At distances of 0.4–1.4 n. mi. the tetroon data yield, on the average, a vertical dispersion varying according to the 0.5 power of the downwind distance. However, this average power varies from a value of 0.6 at the shorter distance to 0.4 at the longer distance. On some flights the power becomes negative, signifying a decrease in vertical dispersion with time and distance. This "pinching effect" is associated with periodicities in the vertical motion and its validity is considered in the next section.

3. As in the case of lateral dispersion, figure 3 shows that the above power decreases more rapidly with downwind distance in stable conditions than in unstable conditions. One would estimate from figure 3 that, over the given distance and for the given height, in the case of vertical dispersion the power varies from about 0.9 in unstable conditions to about 0.4 in stable conditions, thus being considerably more sensitive to stability than the power in the case of lateral dispersion. Once again, the dispersion as a function of distance derived from flight 2 (unstable conditions) and flights 6 and 7 (stable conditions) tends to confirm the finding for flights of equal length (fig. 2).

4. Fluorescent dye released by airplane at Cardington under unstable conditions yields vertical dispersions somewhat less than those obtained from daytime tetroon flights at Yucca Flat, as would be expected owing to the extreme instability at the latter site. The dye released in stable conditions yields vertical dispersions in good agreement with those derived from tetroon flights over the sea in relatively stable conditions and derived from the flight within the nocturnal inversion at Yucca Flat. The vertical dispersion data obtained by Hilst and Simpson [8] under stable conditions also agree very well with vertical dispersions derived from the latter flights.

In order to combine the tetroon-derived data concerning vertical and lateral dispersion and also provide a visual picture of the great difference in dispersion under varying atmospheric conditions, figures 4 and 5 were prepared showing the standard deviations of particle displacement in the lateral and vertical directions at downwind distances of 0.5, 1.0, and 2.0 n. mi. The standard deviations are shown as a function of time for the Yucca Flat data

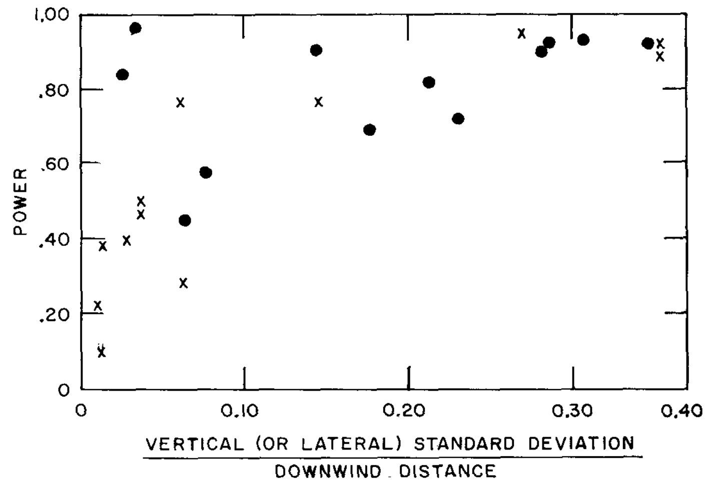

FIGURE 3.—Power of the downwind distance to which the standard deviations of vertical and lateral particle displacement are proportional (ordinate) as a function of the ratio of these standard deviations and downwind distance (abscissa). The dots indicate the respective values for lateral standard deviations, as derived from the tetroon data, the crosses the values for vertical standard deviations.

and as a function of synoptic situation at Wallops Island, with the ordinate also indicating the mean height to which the results apply. The data presented for noon and 3 p.m. at Yucca Flat are the averages of two flights made at the same time but on successive days. Points to be emphasized in figure 4 are:

1. The apparent influence of the ground on the relative magnitude of vertical and lateral dispersion for the two 6 a.m. flights.

2. The evidence that in the morning, when the instability is increasing, the lateral dispersion is greater than the vertical dispersion, whereas at noon the dispersion in the two directions is equal, and in the afternoon the vertical dispersion exceeds the lateral dispersion.

3. The suggestion that in the case of a smoke plume at the given height there would be a reflective effect from the ground during the day, since only the standard deviation of the vertical particle displacement is pictured and thus it is apparent that some particles would intersect the ground at downwind distances of two miles or more.

4. The effect upon contaminant concentration of the different dispersion regimes indicated at noon and 9 p.m., the axial concentration differing by 2–3 orders of magnitude at distances of 0.5–2.0 n. mi.

In the case of dispersion over the sea, as illustrated by figure 5, the most obvious feature is the greater magnitude of the lateral dispersion in comparison with the vertical dispersion, the only exception being warm sector conditions as represented by flight 3*. The large lateral dispersion indicated by flight 1* (cold air) is the result of its partially sampling a cold frontal trough so that the lateral dispersion in this case is more applicable to the synoptic scale than the mesoscale.

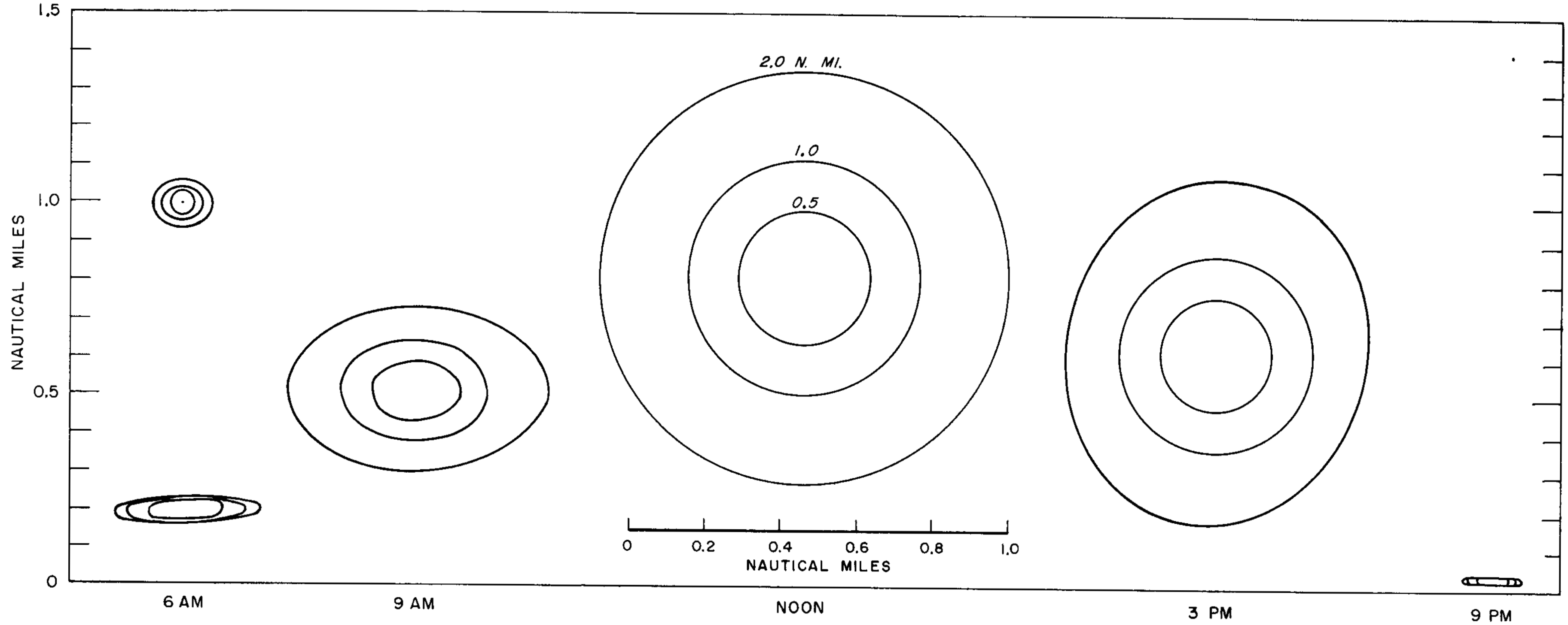

Figure 4.—Standard deviation of vertical and lateral particle displacements as a function of height and time of day for Yucca Flat tetroon flights. The ellipses indicate the standard deviations at distances of 0.5, 1.0, and 2.0 n. mi. Results for noon and 3 p.m. were obtained from averages of two flights at the same times but on successive days.

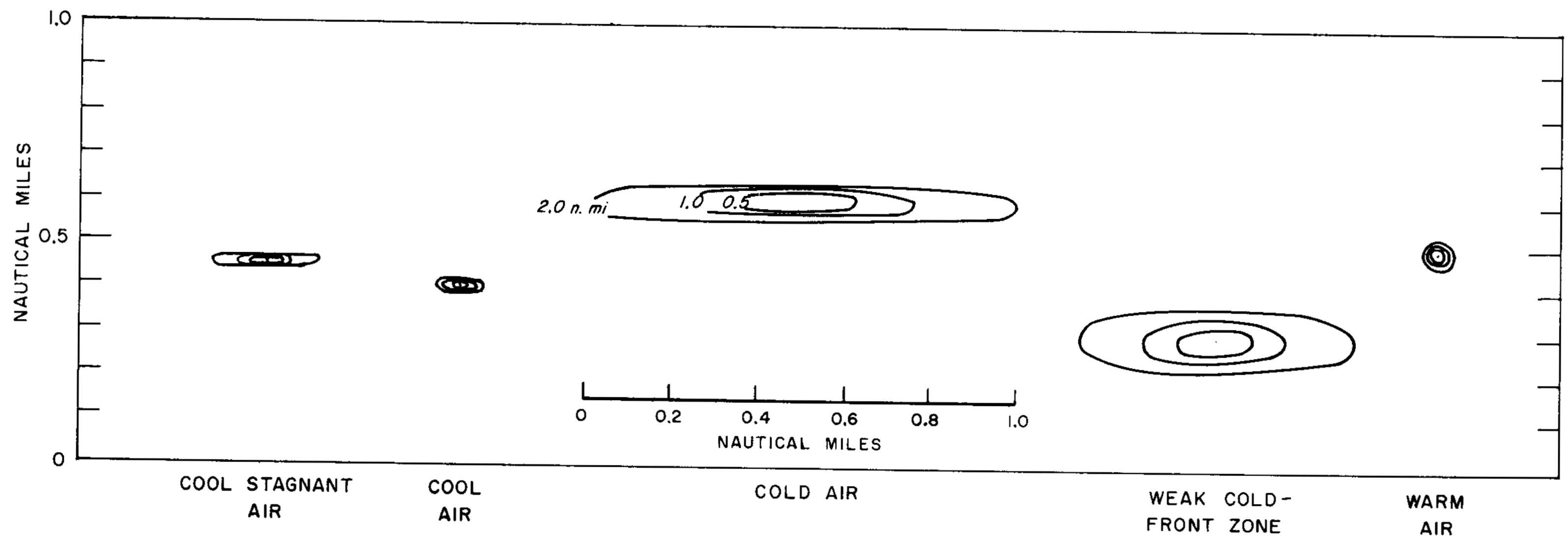

Figure 5.—Standard deviation of vertical and lateral particle displacement as a function of height and synoptic situation for Wallops Island tetroon flights. The ellipses indicate the standard deviations at distances of 0.5, 1.0, and 2.0 n.mi.

TABLE 2.—*Predominant length and time scale of tetroon oscillation in the vertical and lateral dimensions.*

Flight	Vertical dimension		Lateral dimension	
	Length (n. mi.)	Time (min.)	Length (n. mi.)	Time (min.)
1*	2.5	4.2	------	------
3*	3.0, 1.8	10.7, 6.4	1.8	6.4
5*	------	------	------	------
7*	1.8	8.1	1.4	6.3
8*	1.2	12.5	0.4	4.2
1	------	------	------	------
2	------	------	------	------
6	0.6	5.4	------	------
7	1.4	22.8	------	------
9	------	------	------	------
14	3.0	7.5	2.5	6.4
15	------	------	------	------

4. VERTICAL DISPERSION AND PERIODICITIES IN THE FLOW

If there is a periodicity in the flow, the rate of increase of the standard deviation of vertical or lateral particle displacement will not proceed uniformly with downwind distance or time, but rather will possess a relative constriction which approximately indicates the period of oscillation in space or time. Such a feature also carries over into data showing the variation with downwind distance of the ratios of these standard deviations and downwind distance. When, as in figures 1 and 2, such ratios are plotted on log-log paper, the periodicity is approximately indicated by the place where the above ratios decrease most rapidly with distance (slope minima). The periodicity in time may then be derived from the mean velocity along the flight. In table 2 are listed the distances and times (periods) of slope minima as derived from figures 1 and 2. A glance at these figures shows that such slope minima are much more apparent in the case of vertical dispersion than in the case of lateral dispersion. In the former case, in fact, minima in the line slope occasionally are sufficiently pronounced so as to yield an actual, rather than relative, decrease in standard deviation of vertical particle displacement with distance and time (dispersion proportional to a negative power of the distance or time). To the writer's knowledge, Richardson [15] is the only one to have claimed that visual evidence for smoke plume constriction in the vertical exists, and this on a much smaller scale than we are dealing with here. With regard to the reality of these constrictions in the vertical, however, it is suspicious that they are derived only for the relatively short tetroon flights. Flights such as 3* and 7*, which also possess a good periodicity in the vertical, indicate only a slowing down in the rate of increase of cloud depth with distance or time, so that the problem may easily be one of insufficient flight duration. On flights 3*, 7*, 8*, 6, and possibly 14, the vertical periodicities responsible for the constrictions, or tendencies toward constriction, agree closely with the theoretical periodicities to be expected in an atmosphere with the given lapse rate [9].

Inasmuch as there is no theoretical reason why oscillations with such periods should occur in the horizontal plane, some of the differences between figures 1 and 2 are rationalized. In summary, while the vertical constrictions derived from a few of the tetroon flights could well be a consequence of insufficient flight duration, this general problem should be kept in mind, because there is evidence for the existence of vertical periodicities with a basis in theory and it is conceivable that these periodicities are of sufficient magnitude and consistency so as to induce a constriction, or strong tendency toward a constriction, in the standard deviation of vertical particle displacement as a function of downwind distance.

5. THE USEFULNESS OF TETROONS FOR DISPERSION ESTIMATES

It has been shown in the preceding how tetroon flights, perhaps even individual tetroon flights, can provide dispersion estimates on the mesoscale. Let us now consider some of the advantages of this tetroon technique with respect to the more conventional techniques for estimating atmospheric dispersion from a continuous point source.

One of the newest and most promising methods for estimating dispersion from a continuous point source also involves the use of equation (1), but with the substitution of Eulerian (fixed point) rather than Lagrangian velocity fluctuations [7]. Some assumption then has to be made concerning the shape and scale relations between Eulerian and Lagrangian spectra. If such a relation exists, and it varies little with atmospheric stability, wind speed, distance from the source, or other parameters, then this is certainly the way to estimate atmospheric dispersion, Eulerian wind velocities being so easy to obtain. There is accumulating evidence, however, that while the shapes of Eulerian and Lagrangian velocity spectra may be similar, the scale factor (β) between the two spectra varies with stability and perhaps with other parameters as well. At the present time the whole problem is quite confusing, particularly since different investigators find β varying differently with respect to variations in a given parameter, even from the same data. Thus, from Project Prairie Grass data Barad [3] found that β decreased with increasing stability while, from the same data, Panofsky [12] found that β was approximately equal to 5 during the night and 1 during the day.

It is hoped to make some definitive comparisons of Eulerian and Lagrangian scales by flying tetroons past instrumented barrage-balloon cables at Cardington, England. Such an experiment should tell us whether it is feasible to utilize Eulerian data in equation (1) or whether it will be necessary to utilize data of Lagrangian type. In the latter case, one advantage of tetroons in comparison with smoke, fluorescent dye, or other mass-tracer techniques, is that the radar-tracked tetroon tells you how an air parcel got to a certain spot, not just that it got there [11]. In addition, tetroons will yield dispersion estimates over longer distances than smoke plumes and more easily than fluorescent dye or other tracer techniques, although there is the disadvantage that to compute dispersion to, say, 5 mi., one has to track a tetroon from 25–50 mi. Nevertheless, one would anticipate that, through the use of tetroons, a dispersion climatology could fairly easily be developed, whereby the dispersion to be expected at a given site under given conditions of stability, wind speed, wind direction, etc. could be estimated. In the event of an accidental release of contaminant, the tetroon would not only yield the direction of travel of the contaminant but, as indicated above, would also yield an estimate of the contaminant concentration. Of course, in the case of the tetroon, one has to presuppose the existence of a radar net which would be willing and able to track tetroons upon request. Undoubtedly, one of the chief drawbacks to the whole tetroon system involves the method and means of obtaining suitable radar tracking, either for climatological purposes or for singular releases.

6. CONCLUSION

It has been shown that estimates of dispersion from a continuous point source by means of tetroon flights are in reasonable agreement with dispersion estimates obtained by the release of fluorescent dye. Inasmuch as dispersion estimates on the mesoscale can be obtained simply and cheaply through the use of tetroons, it would appear that tetroon flights are a feasible and logical way of estimating atmospheric dispersion, and hence contaminant concentration, on this scale. An additional asset of the tetroons is that they yield directly the trajectory of air parcel or contaminant. If further experiments continue to indicate the applicability of tetroon flights for this purpose, it is suggested that steps be initiated to develop a dispersion climatology utilizing tetroons, and that tetroons be made available for the purpose of tracing and estimating concentration in the event of an accidental release of contaminant.

ACKNOWLEDGMENT

The basic data for this investigation were made available by Mr. D. H. Pack, Chief, Environmental Meteorological Research Project, U.S. Weather Bureau. Long-range correspondence with him helped clarify many aspects of this essentially new technique.

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